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Geomorphological records of extreme floods and their relationship to decadal-scale climate change

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Abstract

Extreme rainfall and flood events in steep upland catchments leave geomorphological traces of their occurrence in the form of boulder berms, debris cones, and alluvial fans. Constraining the age of these features is critical to understanding (i) landscape evolution in response to past, present, and future climate change; and (ii) the magnitude–frequency of extreme, ungauged floods in small upland catchments. This research focuses on the Cambrian Mountains of Wales, UK, where lichenometric dating of geomorphological features and palaeohydrological reconstructions is combined with climatological data and documentary flood records. Our new data from Wales highlight a distinct flood-rich period between 1900 and 1960, similar to many other UK lichen-dated records. However, this study sheds new light on the underlying climatic controls on upland flooding in small catchments. Although floods can occur in any season, their timing is best explained by the Summer North Atlantic Oscillation (SNAO) and shifts between negative (wetter than average conditions with regular cyclonic flow and flooding) and positive phases (drier than average conditions with less frequent cyclonic flow and flooding), which vary from individual summers to decadal and multidecadal periods. Recent wet summer weather, flooding, and boulder-berm deposition in the UK (2007-2012) is related to a pronounced negative phase shift of the SNAO. There is also increasing evidence that recent summer weather extremes in the mid-latitudes may be related to Arctic amplification and rapid sea ice loss. If this is the case, continuing and future climate change is likely to mean that (i) unusual weather patterns become more frequent; and (ii) upland UK catchments will experience heightened flood risk and significant geomorphological changes.

Keywords: extreme floods; lichenometry; SNAO; climate change; Arctic amplification

1. Introduction

Large floods in small headwater catchments of the UK are highly effective geomorphological agents and their past occurrence can be readily identified from field evidence, including boulder berms, debris cones, and alluvial fan deposits (Carling, 1986; Harvey, 1986; Wells and Harvey, 1987; Coxon et al., 1989; Macklin et al., 1992; Merrett and Macklin, 1999; Johnson and Warburton, 2002; Macklin and Rumsby, 2007; Milan, 2012; Foulds et al., 2013). Dating of these features is critical to understanding (i) landscape evolution in response to past, present, and future climate change; and (ii) the magnitude–frequency of extreme, ungauged floods in small upland catchments. The latter is especially important as it allows upland flood records to be extended beyond the typical range of instrumental data (ca. 35 years in the UK; Macdonald, 2013). In small, ungauged mountain catchments, combining geomorphological and documentary data offers a reliable way to investigate longer term changes in extreme weather and flood frequency over the past two to three centuries (Maas and Macklin, 2002; Macklin and Rumsby, 2007; Ruiz-Villanueva et al., 2013). Records of this length are important because short instrumental records do not cover flood-rich periods in the nineteenth century and first half of the twentieth century (Bichet et al., 2013; Foulds et al., 2013). This can, in turn, lead to the underestimation of flood risk (Black and Fadipe, 2009). Indeed, following recent large flood events in the UK (e.g., summer 2007, 2012) reports of their ‘unprecedented’ nature and ‘biggest in living’ memory are common (Foulds et al., 2012). In contrast, analysis of documentary (Macdonald and Black, 2010; Macdonald, 2012, 2013; Pattison and Lane, 2012) and geomorphological records (Macklin and Rumsby, 2007; Foulds et al., 2013) often reveals a different story. That is, large floods have occurred frequently in the past associated with flood-rich periods and variability of the NAO, SNAO, and the frequency/persistence of different Lamb weather types (LWTs; Lamb, 1972), notably cyclonic and westerly flows (Rumsby and Macklin, 1994; Longfield and Macklin, 1999; McEwen, 2006; Macklin and Rumsby, 2007; Macdonald, 2012; Foulds et al., 2013; Wilby and Quinn, 2013).

Although geomorphological methods of flood series extension have been widely used in the British uplands, records for Wales are restricted to a single catchment in the Brecon Beacons (Macklin and Rumsby, 2007) and a series of debris flows in one valley in Snowdonia (Winchester and Chaujar, 2002). The Cambrian Mountains, which form the central uplands of Wales (Fig. 1), have yet to be studied in detail because of their remoteness and difficulties locating and integrating Welsh and English language documentary flood sources. However, the area is susceptible to high rainfall and flooding (Newson, 1975, 1980). Following one such event in June 2012 (Foulds et al., 2012), several small headwater valleys in the area appeared to contain significant evidence of geomorphologically effective historical floods (i.e., lichen-covered boulder berms) requiring further investigation.

The key aims of this study are to (i) elucidate the chronology of these extreme flood events in the Cambrian Mountains; and (ii) identify climatological and meteorological controls on flood generation. The latter aim is central to understanding local to regional scale catchment response to past, present, and future weather extremes, and inherent flood risk. Catchments investigated in this study are much smaller (< 5 km^2) than typical down-scaled regional climate models (25-50 km^2), which have been shown to perform unreliably in small, steep catchments (Smith et al., 2013). These are precisely the areas where damaging flash floods occur, and we advocate in this paper a geomorphological approach to better understand future flood risk in catchments of this nature.

2. Study catchments

The Cambrian Mountains are located in mid- and west Wales, UK (Fig. 1). They include upland plateaux, typically higher than 300 m Above Ordnance Datum (AOD) (maximum relief is 752 m AOD on Pen Pumlumon Fawr), which are dissected by glacial troughs and the headwaters of some of the largest Welsh rivers, including the Hafren (Severn), Gwy (Wye), Rheidol, Teifi, and Ystwyth. This study focuses on the upper reaches of the Afon Ystwyth (Fig. 1), which rises at 535 m AOD and has a catchment area of 191 km^2. In the lowlands, at Pont Llolwyn, Q_{95} and Q_{10} are 0.60 and 14.33 $m^3 s^{-1}$ (drainage area = 170 km^2), respectively, compared to 0.18 and 5.60 $m^3 s^{-1}$ in the uplands at Cwmystwyth (drainage area = 32 km^2) (Afon Ystwyth gauged data are available through National River Flow Archive: www.ceh.ac.uk). Flood hydrographs in small catchments of the Cambrian Mountains are typically very flashy, with short lag times (< 2.5 hours; Newson, 1975).

The climate of the Ystwyth catchment is typically mild and wet. Mean annual rainfall is 1876 mm at Cwmystwyth (301 m AOD) and 1217 mm at Trawsgoed (63 m AOD). Mean annual temperature is 9.9°C in the lowlands, and average annual temperatures at Cwmystwyth are 7.1–9.2°C (meteorological data for the Ystwyth catchment are available through the Met Office: www.metoffice.gov.uk). The Cambrian Mountains tend to be affected by frontal rainfall associated with Atlantic depressions at any time of the year, as well as slow moving, convective summer storms (Newson, 1975, 1980). An average winter may also see several short-lived snow accumulation and subsequent melt events and ca. 60 days of air frost per year at Cwmystwyth. Geologically, the area is dominated by Silurian deposits of the Llandovery series (shales, siltstones, sandstones, and mudstones of the Cwmystwyth Grits Formation).

This study concentrates on a series of boulder berms (Figs. 2A-2C), alluvial fans, and debris cone deposits (Fig. 2D) that were identified within the small, steep, headwater tributaries of Nant Cwm-Du (Lat. 52°21'18'' N., Long. 3°44'40'' W.; area = 0.9 km^2, average channel bed slope = 0.132 m m^{-1}), Nant Gau (Lat. 52°19'57'' N., Long. 3°47'37'' W.; area = 2.7 km^2, average channel bed slope = 0.079 m m^{-1}), and Nant Milwyn (Lat. 52°20'18'' N., Long. 3°46'05'' W.; area = 3.7 km^2, average channel bed slope = 0.096 m m^{-1}), which are northward-draining, left (south) bank tributaries of the Afon Ystwyth, as well as several berm and cone deposits in the upper reaches of the Rheidol and Leri catchments.

3. Methods

3.1. Lichenometry

Lichenometry is a standard and widely used dating technique in geomorphology. Although originally developed to date glacial deposits (Beschel, 1961), the technique has been applied with considerable success to constraining the age of boulder-berm flood deposits in the British uplands (Macklin et al., 1992; Macklin and Rumsby, 2007). In the Cambrian Mountains lichenometry was used to date boulder berms that were identified using a combination of aerial photographs, ground truthing, and geomorphological field mapping at a scale of 1:10, 000. Once identified, all boulders per berm were searched for lichens. A combination of *Porpidia tuberculosa* and *Rhizocarpon geographicum* was used to date surfaces because the former grows relatively quickly (typically > 0.5 mm y^{-1}) and gives high resolution dating for deposits < 75 years in age; beyond this, because of the relatively fast growth rate, lichens tend to coalesce, which prevents measurement. For older deposits, the slower growing *R. geographicum* (typically < 0.5 mm y^{-1}) is capable of giving better dating control, although coalescing lichens and general vegetation growth can still be problematic. In this study, these problems were most apparent in the Nat Gau catchment, where a series of terraced berms (4-5 m above the present channel) could not be dated.

An indirect dating method was used, which relates the size of lichen growing on surfaces of unknown age (e.g., flood deposits) to empirical lichen size–age relationships derived for the same lichen on surfaces of known age (e.g., gravestones) (Macklin et al., 1992; Merrett and Macklin, 1999; Foulds et al., 2013). Local graveyards at Hafod (2-5 km from the study sites) and Ysbyty Ystwyth (5-9 km from the study sites; Fig. 1) were used to construct lichen size–age relationships. The most commonly used lichenometry methods, especially in fluvial studies (Macklin and Rumsby, 2007), involve measurement of the single largest lichen (LL) or the mean of the three or five largest specimens (3LL, 5LL), respectively. For details of other lichenometry methods available to practitioners (e.g., fixed area largest lichen, size frequency, and percentage coverage) see Bradwell (2009).

In order to test which method is the most reliable, calibrated size–age relationships were constructed for LL, 3LL, and 5LL methods. The validity of these lichen size–age relationships was tested by collecting a second batch of *P. tuberculosa* lichen data from independent graveyards and predicting tombstone ages based on the linear regression equations shown in Fig 3A. These dates could then be compared to the true (inscribed) ages (Fig. 3B; Table 1). The 3LL method was selected because of the slightly higher percentage of predictions accurate to > 10 years compared to the 5LL method and the greater accuracy dating older surfaces compared to the LL method (Table 1). The *Rhizocarpon* size–age relationship could not be validated because gravestones with at least three lichens growing on them could not be found in the test graveyards; this was probably owing to differences in microclimate between graveyard sites. In this, study all lichen ages are plotted showing ± 2 σ error bars based on test data for *P. tuberculosa* (Table 1).

3.1.1 Lichen growth rates

Average, minimum, and maximum growth rates for *P. tuberculos*a in the Cambrian Mountains are 1.20, 0.73, and 2.28 mm y^{-1} and 0.42, 0.34, and 0.67 mm y^{-1} for *R. geographicum*. These rates were calculated by dividing average lichen size by gravestone age. The latter was adjusted for lag colonisation periods of ca.10 (*P. tuberculosa*) and ca.15 (*R. geographicum*) years, respectively. These rates are typical for *P. tuberculosa* and *R. geographicum* growing in upland Britain (see Armstrong and Bradwell, 2010; Foulds et al., 2013). Images of these lichen species and habitat details can be found on the British Lichens website (www.britishlichens.co.uk) and in Dobson (2011).

3.2. Palaeohydrological analysis

Relative flood magnitude was assessed by measuring the mean B-axis of the five largest boulders (*Di*) present in each boulder-berm unit. A variety of boulder transport equations can be used to estimate palaeohydrological characteristics, the most commonly used being those of Costa (1983), based on data from the Colorado Front Range. Using this method, average velocity (V; Eq. 1) is calculated from average boulder dimensions (*Di*), and this figure is then multiplied by cross-sectional area to estimate discharge. Perhaps more appropriate in a UK context is the method of Carling (1986), developed from field data in a steep upland catchment in northern England (Eq. 2; Carling, 1983, 1986), an environment similar to mid-Wales, although the streams investigated in the Cambrian Mountains are steeper than those studied by Carling (1983, 1986). In Eq. (2), A, γ, S and n represent cross-sectional wetted area (estimation of palaeostage is described below), specific weight of water, average channel bed slope, and Manning's roughness coefficient, respectively.

$$V = 0.18\, Di^{\,0.487} \qquad (1)$$

$$Q = 3.06 \times 10^{-2}\, A\, Di^{\,-2/9}\, \gamma^{2/3}\, S^{-1/6}\, n^{-1} \qquad (2)$$

$$n = 0.32\, S^{0.38}\, R^{-0.16} \qquad (3)$$

Palaeostage was estimated using berm crest elevation (Carling, 1987; Kehew et al., 2010) and the area between the berm base/floodplain contact and berm crest was estimated as the depth of overbank flow (used to approximate cross-sectional area of flow). Variables of S and A were based on field survey using a differential GPS (Trimble R8), and n values used were 0.05 and 0.07 (i.e., Chow's (1959) normal and maximum values for boulder streams). Roughness was also derived empirically from *S* and *R* (hydraulic radius) (Eq. 3; Jarrett, 1992). The latter method typically gives much higher *n* values, in this case 0.13-0.15, similar to other published values for UK mountain streams (Johnson and Warburton, 2002). Palaeodischarges were only estimated for the Nant Cwm-Du, which has a very simple valley floor relief and morphology (i.e., berms deposited on straight floodplains) suitable for discharge reconstructions. The majority of berms in the other study catchments are located on terraces and associated with palaeochannels, not the modern channel; and thus too many assumptions would need to be made about pre-flood cross-sectional areas to arrive at reliable estimates of discharge.

3.3. Climatological and documentary data

Some of the largest known floods in the British uplands have been caused by near stationary summer thunderstorms that can deliver 100 to > 200 mm of rain in 2-5 hours (Burt, 2005). Atmospheric conditions most favourable to these situations are often associated with meridional flow patterns when the Summer North Atlantic Oscillation (SNAO) (Folland et al., 2009) in its negative mode, which pushes the jet stream and the associated Atlantic storm track farther south than usual (Dong et al., 2013). Folland et al.'s (2009) 'high summer' (July-August) SNAO index data were used to explore longer term changes in summer atmospheric circulation and its potential impact on flood frequency. For the winter half year (October-March), station-based NAO index data were used to examine climate-flood linkages (downloaded from the University of East Anglia's Climatic Research Unit:

www.cru.uea.ac.uk). Known flood dates were also analysed with respect to LWTs based on Jones et al. (2012b).

A documentary flood history (Table 2) was compiled from English and Welsh language newspaper archives and local school logbooks (Parry, 2013). The value of such sources, especially 'grey literature' (Uhlemann et al., 2013), for reconstructing historical climatology and geomorphology has been shown by Brazdil et al. (2006), McEwen and Werritty (2007), and Macdonald et al. (2010). The latter study highlighted the as yet untapped potential of historical documents written in Welsh, particularly where they can be integrated with English-medium sources and instrumental series. However, documentary flood references are often subjective, can exaggerate magnitude, and/or mis-date events (Foulds et al., 2012, 2013). Furthermore, flood impacts are often reported only for large rivers and specifically for infrastructure/property flooding. This can be problematic because a flood that has been documented need not necessarily have been geomorphologically effective. In remote mountain catchments, floods may also go unreported. These factors mean that caution should be taken to not overinterpret historical sources.

4. Results

4.1. Geomorphological-based flood chronology

Figure 4 shows decadal summaries of the total number of channel and slope floods in the Nant Cwm-Du (Fig. 4A), Nant Gau (Fig. 4B) and Nant Milwyn (Fig. 4C) catchments. Overall, these data indicate that the most geomorphologically effective known hydrometeorological conditions occurred in the Cambrian Mountains during the period 1900-1960 (Fig. 4D), although there are variations between the three study catchments. Peak geomorphological activity occurred in the Nant Cwm-Du system in the 1920s (7 berms) and from 1940 to 1960 (14 berms). These dates are similar to the Milwyn catchment, where peak berm deposition occurred in the 1910s (6 units) and two berms in a small tributary of the upper Rheidol (Nant y Llyn) (1905 ±10 and 1945 ±10, respectively). A single berm was also dated to the 1932 ±10 in the upper Leri catchment. In contrast, berms were deposited slightly earlier in the Nant Gau catchment (1860s to 1880s: 2-3 units; 1920s: 3 units). Older deposits in the Nant Gau system correspond with a wider valley floor and a series of terraced berms (Fig. 2C) that predate more recent (floodplain) deposits. Our data suggest that preservation potential in the narrow Nant Cwm-Du and Nant Milwyn catchments is lower than in the Nant Gau catchment because of high rates of valley floor reworking. This means that the alluvial record has been censored (Lewin and Macklin, 2003) and skewed toward the twentieth century; Foulds et al. (2013) reported a similar finding in catchments of < 1.5 km^2 on Dartmoor. Low 'apparent' rates of deposition before 1900 are also a reflection of berms that could not be dated owing to coalescing lichens on older deposits.

In terms of slope activity (Figs. 2D, 4D), the majority of dates correspond with berm deposition between 1900 and 1940, as well as a shallow gully and associated debris cone cut into the back wall of the Cwm dated to 1991 ±10. A gully and debris fan generated by an event in June 2012 was also identified on the Nant yr Hulog, which is a very steep (0.27 m m^{-1}) tributary in the upper Rheidol catchment. Most of the slope failures in June 2012 were disconnected from river channels (see Foulds et al., 2012); this partly explains the small number of berms generated during this event.

Field evidence strongly suggests that berm generation in the study catchments is linked to strong slope-channel coupling through undercutting and bank/slope collapse. In all of the catchments, but especially in the Nant Cwm-Du and Nant Gau, a series of large, vegetated erosional scars indicate past episodes of erosion; some of the most extensive berm deposits can be found downstream of these features (Fig. 5). Low rates of berm deposition in recent decades (post-1960) are mirrored by a lack of recent evidence of high sediment supply from boulder-rich drift deposits. Lichen data suggest that the last large-scale valley floor reactivation phase probably took place sometime in the 1940s/1950s.

4.2. Linking documentary and geomorphological flood records

Our lichen-based chronology points to frequent berm deposition between 1900 and 1960. However, because of dating accuracy limitations, many berm ages overlap, making it difficult to be precise about the timing of flood events. To refine the lichen chronology, documentary sources have been used in an attempt to identify specific flood events (Table 2). Many of the largest floods in small upland UK catchments have been associated with slow moving summer storms (e.g., West Yorkshire, 1944: Doe and Brown, 2005; Lynmouth, 1952: Dobie and Wolf, 1953; North Pennines, 1983: Carling, 1986; Howgill Fells, 1982: Harvey, 1986; Boscastle, 2004: Roca and Davison, 2009). Based on these known flood-triggering conditions, documented events in June 1910, July 1926, June 1931, June 1935, and July/August 1957 (Table 2), all of which refer to torrential thundery rain, are the most likely to have been responsible for boulder-berm deposition in the early to mid-twentieth century. Some especially ‘flood-rich’ years were 1886, 1909, 1910, and 1957 (Table 2); all of these years correspond with decades identified as having high rates of berm deposition (Fig. 4D). Additionally, taking dating errors into account, repeated flooding in 1957 (Table 2) may explain the valley floor reactivation phase sometime in the 1940s/1950s. In terms of slope activity, the deepest gullies and associated debris fans in the Ystwyth headwaters (e.g., Fig 2D) also date to between 1905 ±10 and 1931 ±10; documentary sources also record a large landslide in the upper Ystwyth valley in September 1922 (Table 2). These dates suggest the potential for strong slope-channel coupling in the early twentieth century.

A boulder-berm dated to 1932 ±10 in the upper Leri catchment also corresponds with a severe thunderstorm and flood in June 1935 (Table 2). The potential 1935 berm is significant because at the same site and inset on a lower alluvial unit (floodplain), there is a boulder-berm deposit from June 2012, which has almost identical mean and maximum boulder dimensions to 1935 material (Fig. 6). These data confirm that the June 2012 flood was not 'unprecedented', having very likely occurred at least twice in ca. 77 years.

4.2.1 Flood seasonality

Detailed seasonal analysis of documentary events in the Cambrian Mountains (Fig. 7) shows a sharp increase in flood frequency between 1870 and 1925 (autumn) and from 1870 to 1930 (summer). Winter floods were most common between 1900 and 1910. After 1910 and 1925, autumn and winter flooding declined, although summer flooding continued intermittently up to the 1970s. In comparing berm and documentary flood series, summer and autumn events show the best agreement with high rates of berm sedimentation in the late nineteenth and early to mid-twentieth centuries.

4.3. Palaeohydrology of flood events

4.3.1. Relative flood magnitude

Figure 8 shows proxy flow magnitude based on average boulder dimensions. These data show a marked reduction in flood magnitude between 1850 and present. The largest boulders (0.7-0.9 m) are associated with terraced deposits in the Nant Gau catchment dating to the mid-to-late nineteenth century. Two floods of comparable size to nineteenth century events took place in 1923 ±10 and 1949 ±10. After ca. 1960, flood magnitude declined (average boulder dimensions < 0.5 m; Fig. 8). An important caveat is that using boulder data in this way assumes an unlimited supply of boulders of all sizes through time. If earlier floods had exhausted the largest boulders, there would be a limit to the maximum calibre of sediment available for transport during later floods. This scenario would give an impression of decreasing flood magnitude. However, this is not thought to be the case in the study catchments because (i) large boulders are abundant in all of the present day river channel beds; (2) in the small, narrow catchments of the Cambrian Mountains, large floods would be easily capable of stripping and remobilising boulders associated with historical berm units (e.g., Milan, 2012); and (iii) all of the rivers investigated have a high potential for strong slope-channel coupling as they are deeply incised through boulder-rich drift deposits.

4.3.2. Discharge

Table 3 shows discharge estimates for 29 flood berms in the Nant Cwm-Du catchment based on Carling (1986), Costa (1983), and a variety of *n* values. Notable differences between these *Q* estimates mean that it is necessary to assess which, if any, are the most realistic. Table 4 shows previously published discharge estimates from other small UK catchments, and Fig. 9 shows data from Nant Cwm-Du plotted alongside other UK and European floods. For systems of < 2 km^2 in an upstream catchment area, Table 4 suggests that peak discharges of 4-7 $m^3 s^{-1}$ are realistic. Combining Carling's (1986) method of estimating discharge (Eq. 2) with *n* values derived empirically using Jarrett (1992; Eq. 3) produces similar peak flow estimates (1-7 $m^3 s^{-1}$; Table 3). Table 4 and Fig. 9 also suggest that for the slightly larger Gau and Milwyn catchments, formative discharges may have been in the region of 20-40 $m^3 s^{-1}$. On the upper Leri, Foulds et al. (2012) estimated the 2012 flood at between 21 and 31 $m^3 s^{-1}$ (area = 7 km^2).

Costa's (1983) method produced much higher *Q* estimates (Table 3), as reported in previous research (Carling, 1986; Johnson and Warburton, 2002). These overestimates occur because average water velocities calculated using Costa (1983) are relatively high (> 4 m s^{-1}) and exceed typical flash flood velocities of < 3 m s^{-1} (Marchi et al., 2010; Lumbroso and Gaume, 2012). Carling (1986) estimated an average water velocity of 1.2 m s^{-1} for the Noon Hill event based on the observed flood wave travel time. This compared to velocities > 4 m s^{-1} based on Costa (1983).

4.4. Flood generation and synoptic conditions in the Cambrian Mountains

Table 5 shows the meteorology of documentary floods in the Cambrian Mountains based on LWTs and SNAO/NAO data for three days before and on the flood day. The majority (52%) of historical flood events were associated with cyclonic flow (or some variant thereof; e.g., cyclonic westerly). Other weather types associated with flooding include southerly (19%), westerly (10%), northerly, easterly, and anticyclonic variants (all 6% each) (Table 5). For summer (July-August) events, the strongest control on rainfall and discharge at Cwmystwyth is the SNAO (Fig. 10). Negative SNAO index values correlate with wetter, cooler, and cloudier than average conditions and vice versa for positive index values (Folland et al., 2009). Indeed, many documented summer floods were associated with negative SNAO index values (Table 5). An important exception occurs when warm anticyclonic conditions and positive SNAO index values (associated with the Azores high over the UK) breakdown and very humid air is drawn in from the near continent, sparking severe thunderstorms (e.g., August 1957, 1977: Table 5; June 1910: Table 2).

Monthly NAO values indicate that historical autumn-winter floods occurred during negative phases associated with cyclonic conditions (Table 5), which can give rise to circulating frontal rain bands and documentary references to rainfall continuing over several days (e.g., February 1869, December 1880, and September 1903: Table 2). Positive autumn-winter NAO values are also associated with an increased frequency of westerly/southwesterly winds, which can lead to orographically enhanced daily and multiday rainfall totals in upland areas (Burt, 2005; Burt and Howden, 2013) (e.g., November 1894, 1929, December 1979, March 1998, October 2000: Table 2).

Positive NAO conditions correlate well with average autumn-winter flows at Cwmystwyth and maximum flows in December (Table 6). However, these data should be treated with caution because the gauge record at Cwmystwyth is very short and covers a period of frequent, low magnitude events. Indeed, Table 5 suggests that many historical autumn-winter floods were associated with negative NAO conditions.

4.5. Longer term climatic context of extreme floods in the Cambrian Mountains

In the light of strong correlations between the SNAO, cyclonic weather types, rainfall, river flows, and known extreme flood-generating mechanisms (i.e., summer storms), the full SNAO and cyclonic LWT series can be used as useful proxies for past periods of high rainfall and flooding (Fig. 11), including summer 2012. Figures 11A and 11B show that from 1850 to 1900, from 1910 to 1940, and during the 1950s there were notable negative SNAO anomalies, high cyclonic activity, and rainfall in SW England and Wales. These climatic data correspond well with summary boulder-berm data in terms of peak deposition in the early to mid-twentieth century and peak magnitude in the second half of the nineteenth century and in the ca. 1920s and ca. 1940s. The full SNAO, cyclonic LWT, and SW England and Wales rainfall series provide strong explanations for the sharp decline in boulder-berm deposition and flood magnitude after ca. 1960. After this date, the frequency of positive SNAO anomalies increased, accompanied by a sharp decline in the frequency of cyclonic summer flow and rainfall. Additionally, Fig. 11A highlights the negative shift in the SNAO since 2007, which corresponds with a run of very wet summers in the UK and widespread flooding (including June 2012 in the Cambrian Mountains).

During the autumn and winter, there is some correspondence between the timing of positive NAO phases, high rainfall, documented floods, and berm deposition, especially from 1910 to 1960 (Fig. 11C). However, the average Nov-Feb NAO does not provide an adequate explanation for the sharp decline in boulder-berm sedimentation and flood magnitude in Wales and the wider British uplands during the late twentieth century (Fig. 12; Macklin and Rumsby, 2007). On the contrary, declining berm sedimentation after ca. 1960 in small mountain catchments corresponds to above average autumn-winter rainfall and a well-documented run of positive NAO index values (Fig. 11C; Hurrell and van Loon, 1997; Osborn, 2006).

5. Discussion

5.1. Comparisons with other UK lichen-based flood records

The timing of geomorphologically effective flood events in the Cambrian Mountains has many similarities with previously published lichen-based flood chronologies in the British uplands (Fig. 12). Most notably, geomorphic activity in the Brecon Beacons (south Wales) shows a similar early twentieth century peak, and Winchester and Chaujar (2002) reported peak debris flow activity in Snowdonia (north Wales) between the 1880s and late 1920s, similar to mid-Wales. There is also very good agreement between high rates of berm deposition on Dartmoor (Foulds et al., 2013), in the North Pennines (Macklin et al., 1992), and Yorkshire Dales (Merrett and Macklin, 1999) in the late nineteenth and early twentieth centuries. In terms of flood magnitude, average boulder dimensions were generally declining throughout the 1900s in mid-Wales, very similar to downward trends in flood competence during the twentieth century in other small upland catchments (Macklin et al., 1992; Merrett and Macklin, 1999; Foulds et al., 2013). The abrupt late twentieth century decline in flood activity in the British uplands is probably the greatest area of commonality in all of the respective flood records (Fig. 12).

5.2. Climatological controls on upland flooding

5.2.1. Summer

The timing of geomorphologically effective floods in the British uplands and their large-scale atmospheric context appear to be controlled by negative phases of the SNAO and associated southerly migration of the North Atlantic storm track toward the UK (Folland et al., 2009; Dong et al., 2013). Under these conditions, meridional flow patterns, cyclonic circulation, extreme rainfall, and floods are more frequent (Rumsby, 1991; Macklin et al., 1992; Rumsby and Macklin, 1994; Foulds et al., 2013). Extreme rainfall leads to high rates of surface runoff, which activate hillslope sediment stores and increase sediment supply, owing to effective slope-channel coupling in small, narrow catchments with limited valley floor storage space (Harvey, 1986; Wells and Harvey, 1987).

In contrast, periods of reduced upland geomorphic activity during the late twentieth century (Macklin and Rumsby, 2007) are related to a transition to above average SNAO anomalies since the ca. 1960s, indicating a change toward persistent anticyclonic flow during recent decades (up to ca. 2007) (Linderholm et al., 2008).

Indeed, many instrumental records show reduced summer rainfall and intensity from 1961 to 2000 (Osborn and Hulme, 2002; Wilby et al., 2008; Biggs and Atkinson, 2011; Burt and Ferranti, 2012; Jones et al., 2012a). These dry summer conditions are clearly manifest in the British boulder-berm flood record (Fig. 12), suggesting that although winter floods, especially when combined with snowmelt (Rumsby and Macklin, 1994, 1996; Merrett and Macklin, 1999; Johnson and Warburton, 2002), can initiate appreciable geomorphic changes, the UK boulder-berm record would appear to be a useful proxy of summer climate (high rates of berm deposition = wetter than average summers; low rates of berm deposition = drier than average summers).

5.2.2. Autumn-winter

Winter NAO (Nov-Feb) variability appears to have had less of an impact on small UK mountain catchments because (i) long duration rainfall events generally have lower intensities than short duration convective storms, and (ii) return periods only tend to become extreme for periods > 24 hours (Archer et al., 2005; Walsh, 2010). Whilst capable of wetting slopes to the point of failure, this type of rainfall cannot produce the extreme flood peaks that transform river channels in small catchments (Newson, 1989). In contrast, autumn-winter frontal rainfall during the 1980s and 1990s caused a notable flood-rich period in large UK catchments (McEwen, 2006; Macdonald, 2012; Pattison and Lane, 2012), owing to a prolonged run of positive NAO values (Hurrell, 1995; Hurrell and van Loon, 1997). Asynchrony in the timing of extreme floods in the uplands and lowlands is important because it implies that flood risk associated with future climatic change will vary spatially and temporally, even with different parts of the same river basin.

5.3. Climate change and future floods in the Cambrian Mountains

Smith et al. (2013) suggested that the much quoted ‘wetter autumn-winters/drier summers’ climate change scenario for the UK may be less clear-cut than first thought, and they highlight appreciable variations from catchment-to-catchment, season-to-season, and between seasonal averages and extremes. Most notably, the ‘drier/warmer’ scenario is being complicated by the possible role of Arctic amplification and rapid sea ice loss, which may be directly affecting mid-latitude weather systems (Francis and Vavrus, 2012; Overland et al., 2012; Screen, 2013; Screen and Simmonds, 2013). Specifically, Arctic amplification reduces the equator-pole temperature gradient, which leads to enhanced meridional flow (Overland et al., 2012; Screen, 2013) and causes a southward displacement of the jet stream toward the UK. These conditions favour unusually wet summers in the UK (e.g., 2007-2012) and boulder-berm generation.

Evidence of the ‘wetter autumn/winters’ scenario is apparent in many short instrumental records (Wilby et al., 2008). Although Biggs and Atkinson (2011) reported increasing hydrological extremes in parts of the Cambrian Mountains, the term ‘extreme’ is relative because the period covered in their study (1977-2006) does not include any large historical events (e.g., Table 2). Flow records beginning in the relatively dry 1970s are ‘hard-wired’ to show increased flood risk (Wilby and Quinn, 2013); if longer records were available, the results of Biggs and Atkinson (2011) might turn out to be less significant. In the absence of long instrumental records, other evidence must be used to extend climate/flood records. Geomorphological data, combined with documentary data and longer term atmospheric proxies, are key components to better understanding present and future flood risk in small upland catchments. Indeed, ungauged mountain catchments are a global phenomenon and we are confident that the methods outlined in this paper could be applied beyond the UK or Europe.

6. Conclusions

In upland areas of the UK small, steep, boulder-bed streams are often ungauged. This poses a particular problem because these types of catchment are capable of generating severe floods, with serious consequences for local infrastructure and public safety (e.g., bridge collapse, dam wall integrity). Investigations in mid-Wales showed that coarse-grained flood deposits can be dated using lichenometry to provide a valuable method of extending upland flood records (> 150 years in length). Data sets of this length are critical to fitting short-term instrumental series into their longer term context. Our new data from mid-Wales, combined with previously published data, show that the incidence of extreme flooding in small upland catchments is best explained by the SNAO and shifts between negative (wetter than average conditions with regular cyclonic flow and flooding) and positive phases (drier than average conditions with less frequent cyclonic flow and flooding), which vary from individual summers to decadal and multidecadal periods. Recent wet summer weather, flooding, and boulder-berm deposition in the UK (2007-2012) are related to a pronounced negative phase shift of the SNAO.

Evidence suggests that recent summer weather extremes (2007–2012) in the mid-latitudes are related to Arctic amplification and rapid sea-ice loss, which favours enhanced meridional flow patterns and flooding. This means that future climatic change and accelerated Arctic melting may lead to (i) heightened flood risk, and (ii) appreciable geomorphic changes. In turn, this may also lead to potential sediment management issues in headwater catchments. Finally, based on recent evidence that down-scaled regional climate models perform unreliably in small, mountainous systems (Smith et al., 2013), geomorphologists are well placed to advance our understanding of future climatic changes and their potential impacts on flood risk and landscape change.

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Figure captions

Fig. 1. The upper Ystwyth study area showing locations of the main headwater tributaries where boulder berms have been dated (numbered 1-3). Graveyard locations used to construct lichen size–age relationships (Hafod and Ystbyty Ystwyth) are also shown. Inset map (i) shows the neighbouring upper Rheidol and upper Leri catchments, where a small number of boulder berms and debris cones were identified; this expands to inset map (ii), which shows the wider UK context.

Fig. 2. Examples of geomorphological features dated in the Cambrian Mountains, including boulder berms in the Nant Cwm-Du (2A) and Nant Gau catchments (2B, 2C), and boulder deposits associated with a steep hillslope gully (2D).

Fig. 3. (A) Size–age relationships for *Porpidia tuberculosa* and *Rhizocarpon geographicum* in the Cambrian Mountains; (B) differences between predicted and inscribed gravestone ages (n = 20) based on the size-age regression equation for *P. tuberculosa*. For the 3LL method there was no correlation between lichen size and dating error.

Fig. 4. Summary decadal frequency plots of boulder-berm, fan and cone sedimentation in the Cambrian Mountains. Error bars show two standard deviations based on gravestone age tests (Table 1). It is important to note that low ‘apparent’ rates of berm deposition before 1900 reflect a combination of undateable surfaces

(because of coalescing lichens) and reworking of older deposits by more recent floods.

Fig. 5. View upstream through the middle reaches on the Nant Cwm-Du catchment. In this small system much of the berm material appears to have been sourced from steep and unstable hillslopes, which show evidence of historical erosion, although they are now relatively stable and vegetated.

Fig. 6. Upper Leri catchment showing the active channel (cobble/boulder bed), floodplain and boulders deposited in June 2012 (bag for scale is 0.4 x 0.3 m) and a low terrace and boulder-berm lichen dated to 1932 ±10. At this, point the Leri has a drainage area of 7 km^2 and an average channel bed slope of 0.015 m m^{-1}.

Fig. 7. Cumulative seasonal (DJF, MAM, JJA, SON) plots of documentary floods reported in Table 2 and overlaid with lichen dates for all floods (channel and slope).

Fig. 8. Relative flood magnitude based on average B-axis measurements (*Di*) of the five largest clasts present in each boulder-berm.

Fig. 9. Nant Cwm-Du discharge estimates based on Carling (1986) with roughness derived from Jarrett (1992) plotted alongside European and UK extreme flood estimates for catchments of < 50 km^2 drainage area.

Fig. 10. Correlations between July-August rainfall (A), average and maximum gauged daily flows (B, C), and the SNAO index of Folland et al. (2009) at Cwmystwyth. Rainfall data cover the period 1961-2010 and flow data 1984-2011. Coefficients of correlation (*r*) are also shown where single and double asterisks indicate significance at p = <0.05 and p = <0.01, respectively.

Fig. 11. Summary decadal frequency plots of all dated geomorphological features in the Cambrian Mountains plotted against (A) July-August SNAO index; Folland et al., 2009); (B) July-August frequency of cyclonic LWTs and smoothed July-August rainfall in Southwest England and Wales (SWEP), based on Alexander and Jones (2001), and (C) average November-February NAO index and smoothed total November-February rainfall (SWEP). Low ‘apparent’ rates of berm deposition before 1900 reflect a combination of undateable surfaces (owing to coalescing lichens) and reworking of older deposits by more recent floods.

Fig. 12. Decadal frequency plots of all lichen-dated boulder berms (channel floods) in Wales and England. The dashed line indicates low data quality/no data associated with berms that are either vegetated or beyond the age range of lichenometry (typically very large coalesced specimens). The original North Pennines plot (Macklin et al., 1992) has been updated with data from an extreme flood in 2007 (Milan, 2012).

Table 1

Accuracy statistics of LL (largest lichen), 3LL, and 5LL (mean of the 3 and 5 largest specimens) lichen size–age curves for *Porpidia tuberculosa* based on surface age predictions of gravestones

Statistic	Maximum lichen	Mean of 3 largest lichen	Mean of 5 largest lichen
Maximum accuracy (yrs)	Exact year	Exact year	Exact year
Minimum accuracy (yrs)	32	20	19
Mean accuracy (yrs)	9	9	10
Standard deviation (yrs)	8	5	5
% Predictions $\geq$ 5 years accuracy	40	20	20
% Predictions $\geq$ 10 years accuracy	55	65	55
% Predictions $\geq$ 15 years accuracy	85	90	90

Table 2

Documentary flood events in the Cambrian Mountains, 1842-2012[a]

Date	River / catchment / area	Rainfall	Flooding	Reference
Sep 1842	Rheidol	-	'..a noise was heard resembling that of distant thunder…a tremendous body of water was seen rolling several feet above the waters of the River Rhydol, stripping the fields of hay, wheat, oats and barley.'	The Examiner (1842)
30th Jul 1846	Rivers draining Mynydd Bach – Aeron, Arth, Peris, Cledan	Heavy & localised rainfall over Mynydd Bach area of south Ceredigion	'One of the most dreadful floods that ever occurred in the principality took place on Thursday night in Cardiganshire.' Bridges destroyed & two known fatalities.	Cambrian (1846), Jones (2013)
Mid-Nov 1852	Ystwyth, Rheidol	*'Y mae cymaint o wlaw wedi disgyn yn y mis a aeth heibio*…' (so much rain has fallen in this last month).	'the Ystwyth and Rheidol rivers have overflowed their banks and produced great destruction…'	The Times (1852), *Seren Cymru* (1852)
7th/8th Feb 1869	Severn, Vyrnwy, Dyfi & southern Snowdonia area.	'a strong wind from the SW set in and continued during the whole of Sunday, accompanied with an almost incessant rainfall.'	'For a distance of 7-8 miles there was nothing visible but one great sheet of water, which submerged the lowlands to a depth of 7-8 feet, carrying away in its course a great quantity of wreck.'	Cambrian News (1869)
30th/31st Oct,	Ystwyth, Rheidol,	'unusually heavy rain…'	'The depth of water was in some parts between 5-6 feet…Several wooden	Cambrian News (1870), Aberystwyth

[a] Newspaper and archival references are given in a separate bibliography at the end of this article. *British Rainfall* entries can be accessed via a digital archive (www.badc.nerc.ac.uk; Rodda et al., 2009). Where references to specific properties are made in school log books, these have been anonymised with [blank].

1870	Severn		bridges were carried away'. 'Such a flood has not been witnessed in this town during the memory of that often quoted individual "the oldest inhabitant".'	Observer (1870)
Late Jan 1876	Ystwyth	-	'Attendance fell off this week owing to the unusual severity of the weather. The children cannot attend as the rivers are continually flooded.'	Cwmystwyth School Log Book (1876)
Late Aug/early Sep 1877	Teifi, Wye, Tywi	-	'The extensive damage to property wrought in recent weeks by the large floods in the south call for attention and sympathy throughout the country.'	*Seren Cymru* (1877)
10th Nov 1878	Rheidol, Ystwyth, Aeron	-	'The heavy floods on Sunday carried away two wooden foot-bridges on the Ystwyth and Aeron. The Rheidol, and all other Welsh rivers, were swollen and overflowed their banks.'	Aberystwyth Observer (1878a, b)
16th/17th Aug 1879	Ystwyth, Rheidol, Aeron, Teifi	'a storm of unprecedented severity' 'for nearly 24 hours the rain did not cease falling.' Widespread totals of 60-75 mm.	'..the greatest flood here within the memory of the present generation. It exceeded the flood at the beginning of November last…'	Aberystwyth Observer (1879), *Seren Cymru* (1879), British Rainfall
22nd Dec 1880	Ystwyth, Rheidol, Aeron	'Heavy rains had fallen for two or three days previously.'	'The "oldest inhabitant" of Aberystwyth will have his memory seriously taxed to recall a flood of such magnitude as that which visited the town on Wednesday evening.' Reports of bridges on Ystwyth and Rheidol destroyed.	Aberystwyth Observer (1880, 1881a, b), *Gwyliedydd* (1881)

10th Sep, 1886	Brenig	-	'Residents awoke terrified by the noise of water entering their homes. In a short time the whole of Tregaron was covered by water, measuring 4-5 feet in depth.'	Dydd (1886)
15/16th Oct 1886	Rheidol, Ystwyth, Teifi, Leri, Dyfi	Daily total of 97 mm at Cwmsymlog	The 'Great Storm' of October 1886. 'Trefechan bridge has stood the test of many storms of wind and flood, but that of Saturday morning proved one too many for it.' Felin Newydd bridge also destroyed.	Cambrian News (1886a), Aberystwyth Observer (1886a)
21st Dec 1886	Brenig	-	The thaw of snow which set in swelled the River Brenig to such an extent that it overflowed, covering the whole town with a great depth of water.	Aberystwyth Observer (1886b)
25th – 26th Mar 1889	Ystwyth, Rheidol	'Rain must have fallen heavily on the hills on Saturday and Sunday…'	'….the rivers Ystwyth and Rheidol were greatly flooded on the following days.'	Aberystwyth Observer (1889)
15th Nov 1894	Ystwyth	50-75 mm of rain over parts of the Cambrian Mountains.	'Morning train out of Aberystwyth unable to proceed over Llanilar flats. Traffic resumed later that morning.'	Aberystwyth Observer (1894), British Rainfall
11th-12th Jun 1898	Tregaron area	'..great heat prevailed…the sky became overcast…vivid flashes of lightning and peals of thunder… the rainfall was very heavy in many districts.'	Heavy floods between Tregaron and Derry Ormond.	Aberystwyth Observer (1898)
5th Jan 1903	Ystwyth	-	'Raining very heavily; great floods in the rivers so that the number of children present was only 64.'	Llanilar School Log Book (1903)

10th Sep1903	Rheidol (and Ystwyth)	'The rain which fell almost continuously from Monday afternoon until early this morning…'	'…resulted in the flooding of local rivers. Soon after 5 am the Rheidol valley was flooded and the whole of the meadows were underwater by 8 am; waters had subsided by mid-day.'	Aberystwyth Observer (1903)
15th Jul 1909	Rheidol, Leri	-	'..It is stated that this was the largest flood since the bridges were carried away 18 years ago, but others say there was a similar flood 12 years ago..'	Cambrian News (1909), Aberystwyth Observer (1909), Elerch School Log Book (1909)
28th Sep, 1909	Leri	-	'Two children from [*blank*] have been absent since Tuesday, owing to the river being swollen.'	Elerch School Log Book (1909)
2nd Dec 1909	Severn	'On Wednesday and Thursday torrential rain fell over Newtown and the neighbourhood.'	'On Thursday morning the downpour in the upper Severn valleys caused the river to rise rapidly; in the early hours of Friday morning it had risen 6-7 feet above its normal level.'	Montgomeryshire Express and Radnor Times (1909)
11th Feb 1910	Ystwyth	-	'Attendance for the week has been affected by a flood in the river.'	Llanilar School Log Book (1910)
7th Jun 1910	Aberystwyth, Tregaron, Llangurig	'The wind switched to the southeast; hot, stale air from Russia & Germany flooded the country. Torrents of rain fell – ca. 45 mm in Aberystwyth. Over the Plynlimon range totals were probably in the order of >50 mm in 12 hours.'	Severe thunderstorms; 'much flooding has been caused and roads have been rendered impassable.' Great floods experienced on the Teifi.	Cambrian News (1910a)

7th Dec1910	Severn	'Rain continued to fall, until the total amount for the 36 hours ending 6 pm was 55 mm.'	'Such a great weight of rain as recorded for Thursday has naturally led to extensive floods.'	Aberystwyth Observer (1910)
12th Dec1910	Brenig	'A sudden storm passed over the district on Monday night. Flashes of lightning were followed by heavy peals of thunder. Heavy showers of hail and rain fell afterwards….	'… the River Brenig flooded. There was a similar storm on Tuesday night.'	Cambrian News (1910b)
13th Nov 1911	Rheidol, Teifi	-	After an Indian summer the weather changed in November. The Rheidol valley was inundated and the main road Pwllhobi was flooded. Section of the light railway washed away.	Cambrian News (1911)
10th Jun 1913	Ystwyth	-	'Last night and this morning witnessed very heavy rain and floods in the district; very few children present.'	Cwmystwyth School Log Book (1913)
12th Mar 1919	Ystwyth	-	'Owing to stormy weather and floods only 21 children attended school.'	Llanfihangel School Log Book (1919)
12th Jun 1919	Rheidol, Leri	91 mm at Strata Florida, 104 mm at Devil's Bridge, 75 mm at Gogerddan & 87 mm at Tal-y-bont. '..a severe westerly gale, unusual and unexpected in June..'	'The Leri overflowed, causing much damage.' '..the Rheidol overflowed, flooding adjacent meadows.'	Cambrian News (1919), Welsh Gazette (1919)
3rd Nov 1921	Cwmystwyth	-	"Attendance is very good this week with the exception of *[blank],* who experience great trouble from	Cwmystwyth School Log Book (1921)

			dangerous floods on the mountain side. On Thursday 3rd of this month, their father had to come to their assistance before they could get home."	
19th Sep 1922	Rheidol, Severn	'A large and deep cyclonic disturbance.' 36 mm of rain at Aberystwyth; heavy rain and floods reported in west and north Wales.	The Rheidol overflowed into the streets of Aberystwyth and a big landslide was reported on Plynlimon; a bridge over the Rheidol at Capel Bangor collapsed. 'The country around Strata Florida was a scene of devastation.' One fatality near Machynlleth.	The Times (1922), Cambrian News (1922)
2nd Jun1924	Leri	'Exceptionally heavy rain.'	'One of the bridges across the river is not very safe.'	Elerch School Log Book (1924)
21st Jul 1924	Leri	'An exceptionally wet morning again; it has rained heavily in the night and continues to do so.'	'17 children present in the morning, 21 in the afternoon.'	Elerch School Log Book (1924)
18th Jul 1926	Leri	'one of the worst thunderstorms in living memory'. 75-100 mm over Cambrian Mountains east of Aberystwyth.	'The river is flooded…'	Elerch School Log Book (1926), British Rainfall
6th Sep 1927	Leri	0.85 inches (22 mm), Aberystwyth	-	Interview with Tal-y-bont resident (Parry, 2013)
14th/15th Nov, 1929	Leri, Ystwyth	-	'The floods have washed away the bridge from the river near [*blank*]…'	Elerch School Log Book (1929)

28th Mar, 1930	Leri	-	'The children of [*blank*] cannot come to school because the bridge near their house has been washed away…'	Elerch School Log Book (1930)
14th Jun 1931	Severn	Mid-Wales was this afternoon visited by a great thunderstorm which caused serious and widespread havoc. In less than two hours rain had fallen in such a deluge…'	Roads flooded and pavements damaged.	The Times (1931)
25th Jun 1935	Rheidol, Leri	'On 25th June a depression over the Bay of Biscay moved northwards accompanied by heavy rain/thunder. Totals of 70 mm & 83 mm from 15.00 to 20.00.	'A terrible thunderstorm accompanied by torrential rain and lightning– river flooded and bridges swept away.'	British Rainfall; Welsh Gazette (1935) Cambrian News (1935), Elerch School Log Book (1935)
14th Dec 1936	Ystwyth	-	'Very inclement weather – wet, stormy – floods. Children present = 11/46.'	Llanafan School Log Book (1936)
31st Jul 1939	Ystwyth	-	'Most inclement weather and in many cases the river had flooded so that several pupils could not attend.'	Llanafan School Log Book (1939)
4th Nov1940	Ystwyth	-	'Heavy rain has caused the Ystwyth to overflow and the 3 pupils who live on the other side of the river cannot attend.'	Llanilar School Log Book (1940)
18th Mar 1947	Ceredigion & Powys; Dyfi, Teifi	Severe blizzards and deep snow drifts in mid-March gave way to milder air and	'Due to the rapid thaw and heavy rainfall, hundreds of acres of farmland have been inundated. In Cardiganshire, considerable flooding	Cambrian News (1947)

		heavy rainfall.	resulted.'	
11th Jan 1948	Teifi, Severn, Vyrnwy	Severe floods occurred after heavy rain.	Inhabitants of the lower Teifi valley were forced to move their belongings to higher ground.	The Times (1948)
26thJul 1957	Rheidol	-	'The thunderstorm which swooped on Cardiganshire left a trail of havoc. Floodwater 5 feet deep in places. A landslide blocked the old coach road between Cwmystwyth and Rhayader.'	Cambrian News (1957)
5th Aug 1957	Cambrian Mountains	Thunderstorms & 88 mm of rain at Gwngu. 102 mm in 2 hours near Llangurig.	'Sheep and cattle washed away and drowned as streams rose rapidly following exceptionally heavy rain'.	British Rainfall, Newson (1975)
25th Sep 1957	Cambrian Mountains	38 mm at Aberystwyth	'Llandrindod Wells was cut off by floods and three landslides last night…after the heavy rains the mountain streams were swollen to many times their usual size'.	The Times (1957)
12th Dec 1964	Ystwyth, Rheidol, Leri, Dyfi, Tywi, Conwy	122 mm at Cwmystwyth	A 'night of terror' in the Ystwyth valley. Bridges and roads washed away and several large landslides. Weir at Tal-y-bont destroyed.	Cambrian News (1964), *Y Cymro* (1964)
5th Aug 1973	Rheidol, Clarach	'Three and a half inches fell in two days' in Aberystwyth.	Railway embankments and road bridges damaged.	Cambrian News (1973); Newson (1980)
15th Aug 1977	Upper Severn & Tallwyth	Highly localised thunderstorm - 90 mm in 2 hours.	Highly localised flood. Redistribution of gravel and cobble shoals.	Newson (1980)
11th May 1979	Clarach, Peithyll, Ceulan, Leri	'…heavy rain fell in the Aberystwyth area all day and	-	*Y Tincer* (1979), *Papur Pawb* (1979)

		night on 10th…'		
5th Dec 1979	Aeron	-	'…roads were flooded in Dyfed, and in Aberayron four feet of water swamped houses.'	The Times (1979)
18th Oct1987	Aeron	-	Worst flood since 1960	Cambrian News (1987)
6th Mar 1998	Rheidol, Ystwyth, Clarach, Dyfi, Severn	-	'…trains in and out of Aberystwyth were cancelled…'	Cambrian News (1998)
30th Oct 2000	Ceulan, Rheidol	-	Although several roads flooded in Aberystwyth, flows on the lower Leri/upper Wye were 3.5 to 5.0 times lower than maximum recorded values.	Cambrian News (2000)
8th June 2012	Leri, Rheidol, Clarach	Maximum daily fall of 146 mm in the Rheidol catchment. 160 mm in 24 hours on Pumlumon.	Widespread and locally severe flooding in west Wales. Leri, Rheidol and Clarach worst affected.	Cambrian News (2012); Foulds et al., (2012)

Table 3

Discharge estimates for 29 boulder berms in the Nant Cwm-Du catchment based on Costa (1983), Carling (1986), and a variety on *n* values

Method	Q mean (m^3 s^{-1})	Q range (m^3 s^{-1})
(1) Carling (1986); n = 0.05	9 ± 4	4 – 19
(2) Carling (1986); n = 0.07	7 ± 3	3 – 14
(3) Carling (1986); $n = 0.32\ S^{0.38}\ R^{-0.16}$ (Jarrett, 1992)	3 ± 1	1 – 7
Mean of methods 1, 2 & 3	6 ± 3	3 – 13
(4) Costa (1983); $Q = VA$ ($V = 0.18\ Di^{0.487}$)	33 ± 17	10 – 73

Table 4

Flood discharges in small UK catchments compared to estimated values in the Nant Cwm-Du catchment using a combination of Carling (1986) (*Q*), and Jarrett (1992) (*n*)

Flood location and date	Drainage area (km^2)	Q (m^3 s^{-1})	QU (m^3 s^{-1} km^2)	Reference
West Stream, Dorset, May 1986	0.80	7	8.8	Acreman (1989)
Afon Tanllwyth, Cambrian Mountains, Aug 1973	0.89	2.16	2.4	Newson (1975)
Nant Cwm-Du, Cambrian Mountains	0.90	1-7	1.1–7.8	This study
Nant Iago, Cambrian Mountains, Aug 1973	1.02	5.65	5.5	Newson (1975)
Raise Beck, Lake District, Jan 1995	1.27	4–6	3.2–4.7	Johnson and Warburton (2002)
Jordan River, Boscastle, Aug 2004	2.30	20	8.7	Roca and Davison (2009)
West Grain, North Pennines, Jul 1983	3.92	16-22	4.1–5.6	Carling (1986)
Ireshope Burn, North Pennines, Jul 1983	5.93	35	5.9	Carling (1986)
Langdon Beck, North Pennines, Jul 1983	7.14	30	4.2	Carling (1986)
Upper Wye, Cambrian Mountains, Aug 1956	10.6	69	6.5	Environment Agency (2013)
Thinhope Burn, North Pennines, Jul 2007	12.0	60	5.0	Milan (2012)

Table 5

Documentary flood dates (taken from Table 2) and corresponding NAO/SNAO index and LWT values for three days before and on the day of flood (the latter indicated by bold values)

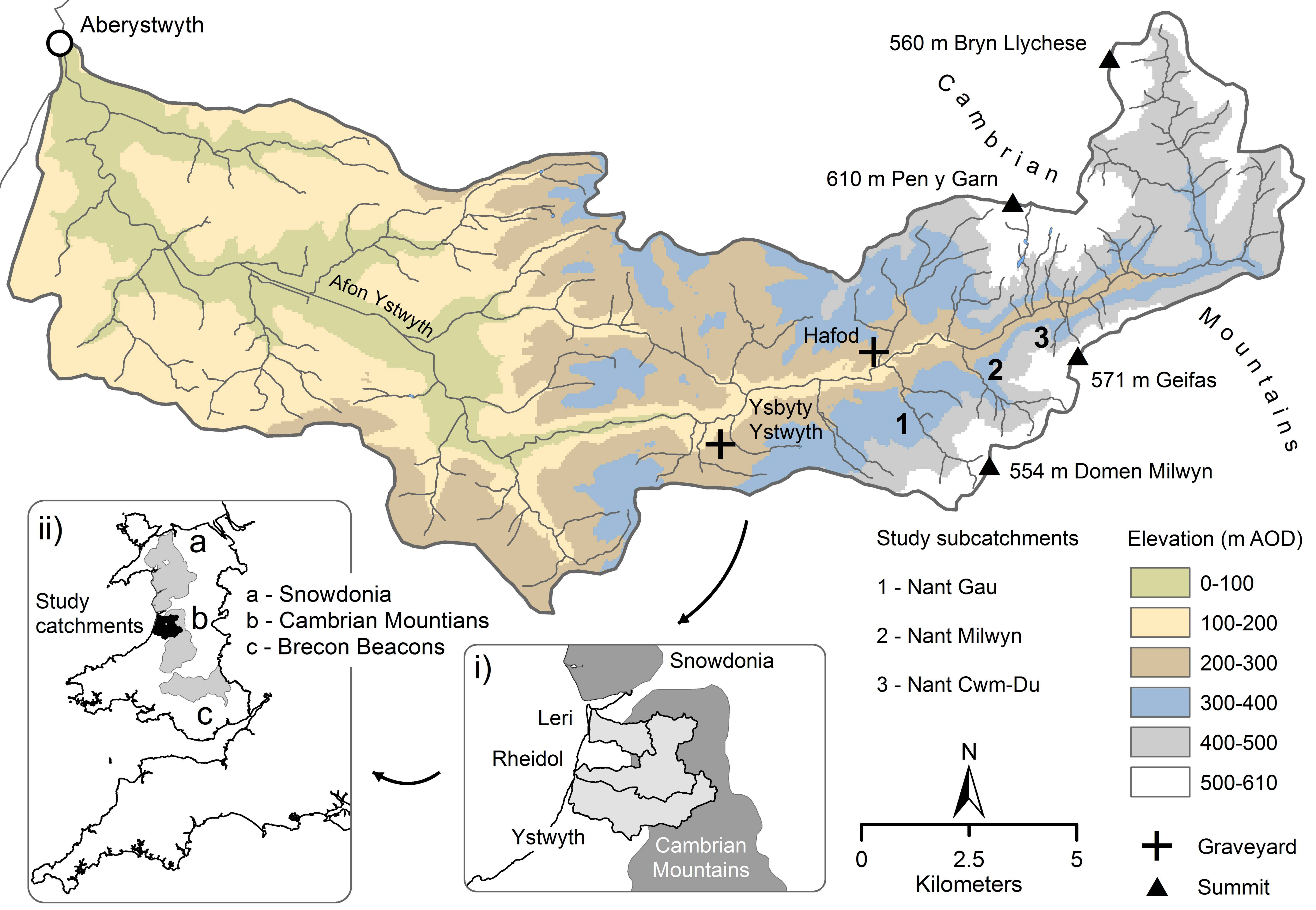
Flood date	NAO	LWT
Sep 1842	-	-
30/08/1846	-	-
15/11/1852	-0.93	-
7-8/02/1869	3.90	-
30-31/10/1870	1.3	-
Jan 1876	1.1	-
Aug/Sep 1877	-0.20/-3.74	-
10/11/1878	-3.47	N, CN, NW, **C**
16/08/1879	-0.54, 0.43, 0.62, **-0.24**	SW, A, CNE, **C**
22/12/1880	0.52	C,C,A,**CS**
10/09/1886	-	SW, SW, SW, **W**
15/10/1886	-0.55	C, CNW, W, **C**
21/12/1886	0.12	N, CNE, A, **SW**
25/03/1889	0.11	A,A,A,**AW**
15/11/1894	1.96	SW, S, C, **S**
11/06/1898	-	ASE, A, AE, **AE**
05/01/1903	1.28	C, CW, W, **S**
10/09/1903	-0.27	C, A,C, **C**
15/07/1909	-1.15, -0.91, -0.56, **-0.56**	ANW, W, W, **W**
28/09/1909	-0.52	AE, A, ASE, **SE**
02/12/1909	-0.48	CSW, C, C, **C**
11/02/1910	3.85	N, A, SW, **W**
07/06/1910	-0.38	CE, E, E, **E**
13/11/1911	-0.05	N, CSE, C, **C**
10/06/1913	0.70	CW, W, W, **NW**
12/03/1919	-0.25	CW,CSW, CW, **NE**
12/06/1919	-0.55	SW, A, SW, **C**
03/11/1921	-1.22	W, ANW, A, **CW**
19/09/1922	-0.43	W, CNW, AW, **CW**
02/06/1924	-0.21	C, CE, C, **NW**
21/07/1924	-1.12, -0.67, -0.12, **0.44**	NW, NW, -, **ANE**
18/07/1926	-0.10, 0.18, 0.19, **0.02**	A, A, A, **SE**
06/09/1927	-0.59	A, S, CSE, **C**
28/03/1930	-0.70	W, A, A, **SW**
15/11/1929	2.15	W, CNW, C, **S**
14/06/1931	-0.40	SW, A, AS, **C**
25/06/1935	0.05	S, A, NE, **E**
14/12/1936	2.37	SW, CW, SW, **C**
31/07/1939	-1.15, -1.72, -1.48, **-1.05**	S, CSW, C, **CW**
04/11/1940	1.30	SW, SW, CW, **C**
18/03/1947	-1.28	S, C, AS, **CSE**
11/01/1948	1.53	NW, CS, S, **C**
26/07/1957	0.16, -0.19, -0.62, **-1.16**	NW, ANW, SW, **CW**
05/08/1957	1.25, 1.11, 1.11, **1.25**	A, A, SE, **SE**,
25/09/1957	-0.68	SE, CE, SE, **E**
12/12/1964	-1.24	W, SW, ASW, **W**
05/08/1973	-0.01, -0.17, -0.95, **-1.81**	C, CSW, C, **C**
15/08/1977	1.52, 1.67, 2.14, **2.54**	A, ASE, SE, **SE**
11/05/1979	-0.01	C, A, S, **CW**
05/12/1979	2.07	W, SW, SW, **W**
30/12/1986	3.42	N, W, W, **C**
18/10/1987	-0.80	C, C, SW, **CS**

06/03/1998	1.24	C, C, W, **CS**
30/10/2000	2.26	W, C, CSW, **C**
08/06/2012	-1.16	S, C, C, **C**

Table 6

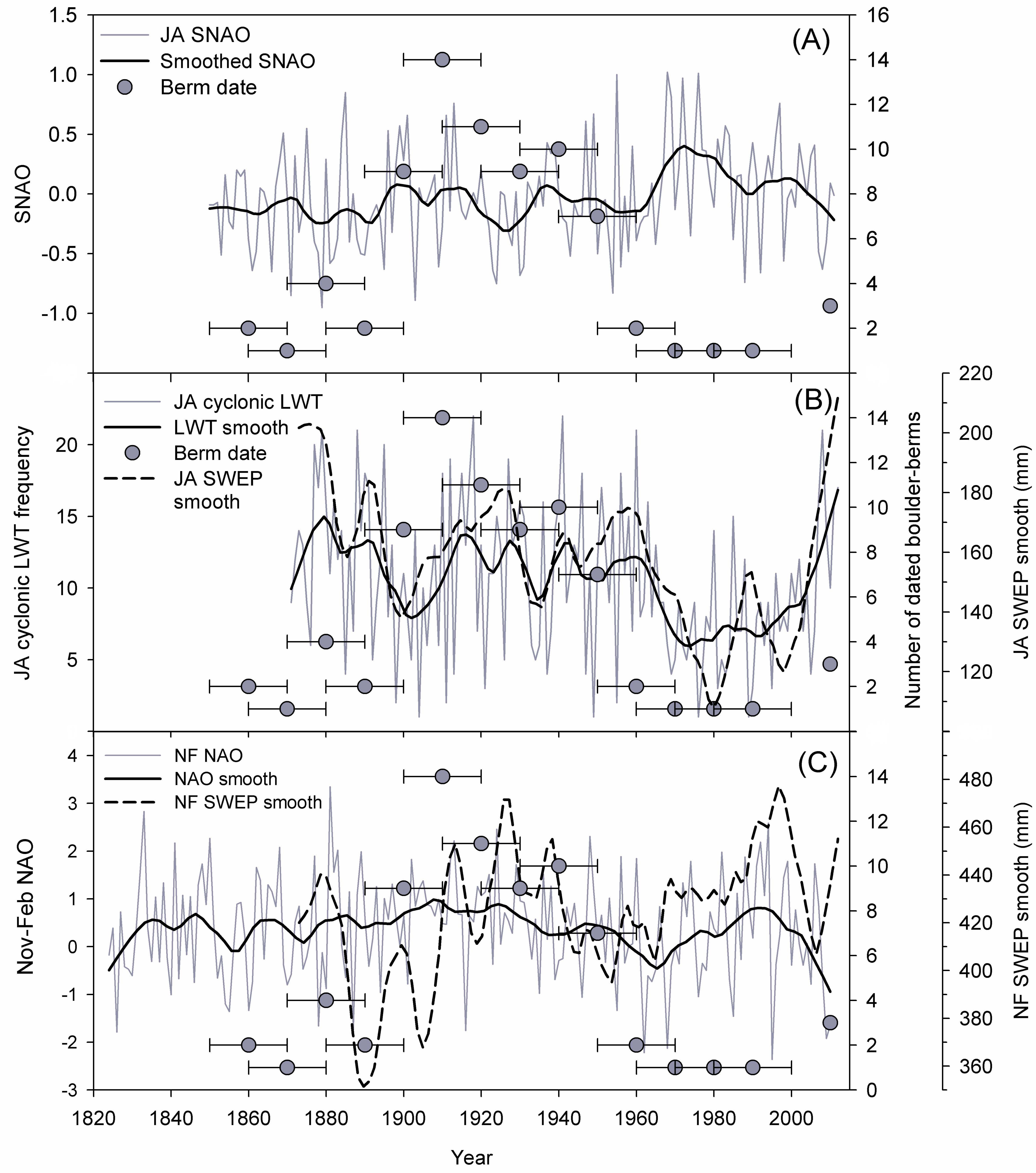
Statistically significant correlations (p = < 0.05) between November-February rainfall, average and maximum gauged daily flows at Cwmystwyth (1984-2010). NS = not significant

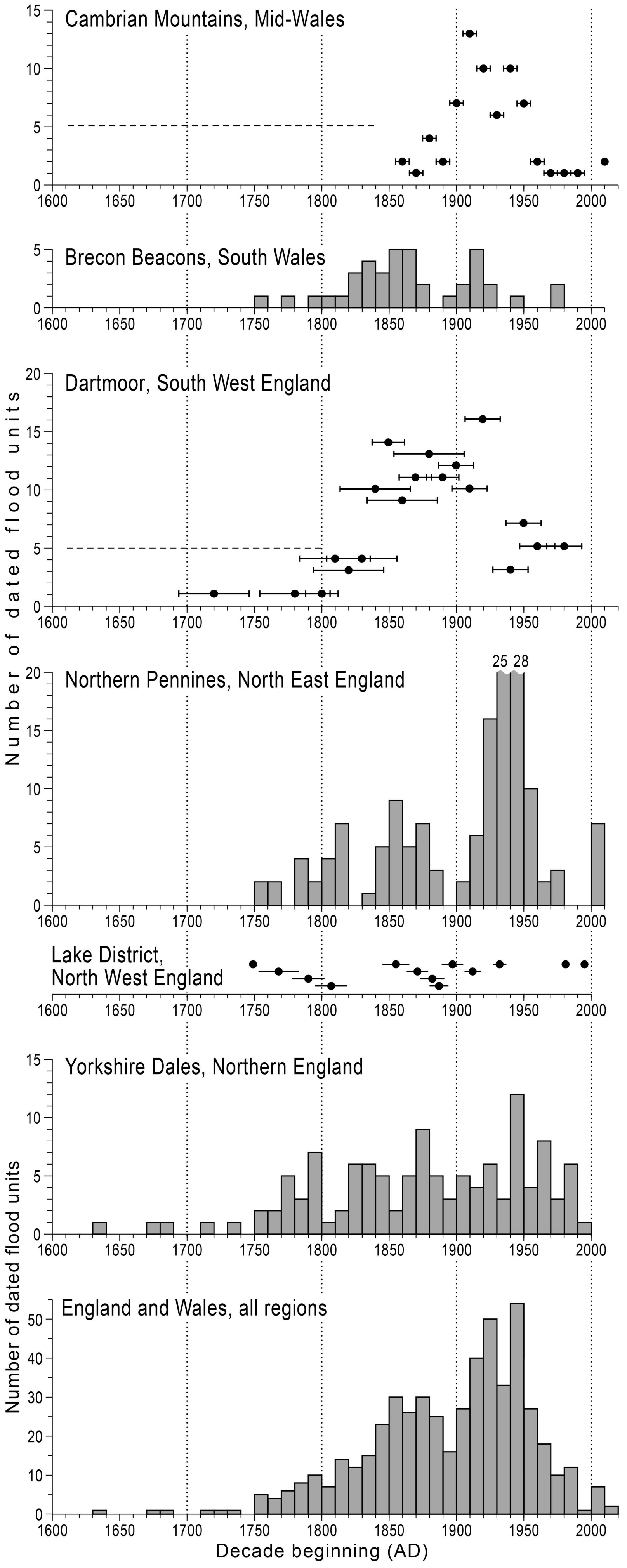
	Jan NAO	Feb NAO	Nov NAO	Dec NAO
Jan *P*	0.642	-	-	-
Jan ave. *Q*	0.644	-	-	-
Jan max. *Q*	NS	-	-	-
Feb *P*	-	0.586	-	-
Feb ave. *Q*	-	0.599	-	-
Feb max. *Q*	-	NS	-	-
Nov *P*	-	-	0.450	-
Nov ave. *Q*	-	-	0.443	-
Nov max. *Q*	-	-	NS	-
Dec *P*	-	-	-	0.577
Dec ave. *Q*	-	-	-	0.713
Dec max. *Q*	-	-	-	0.547



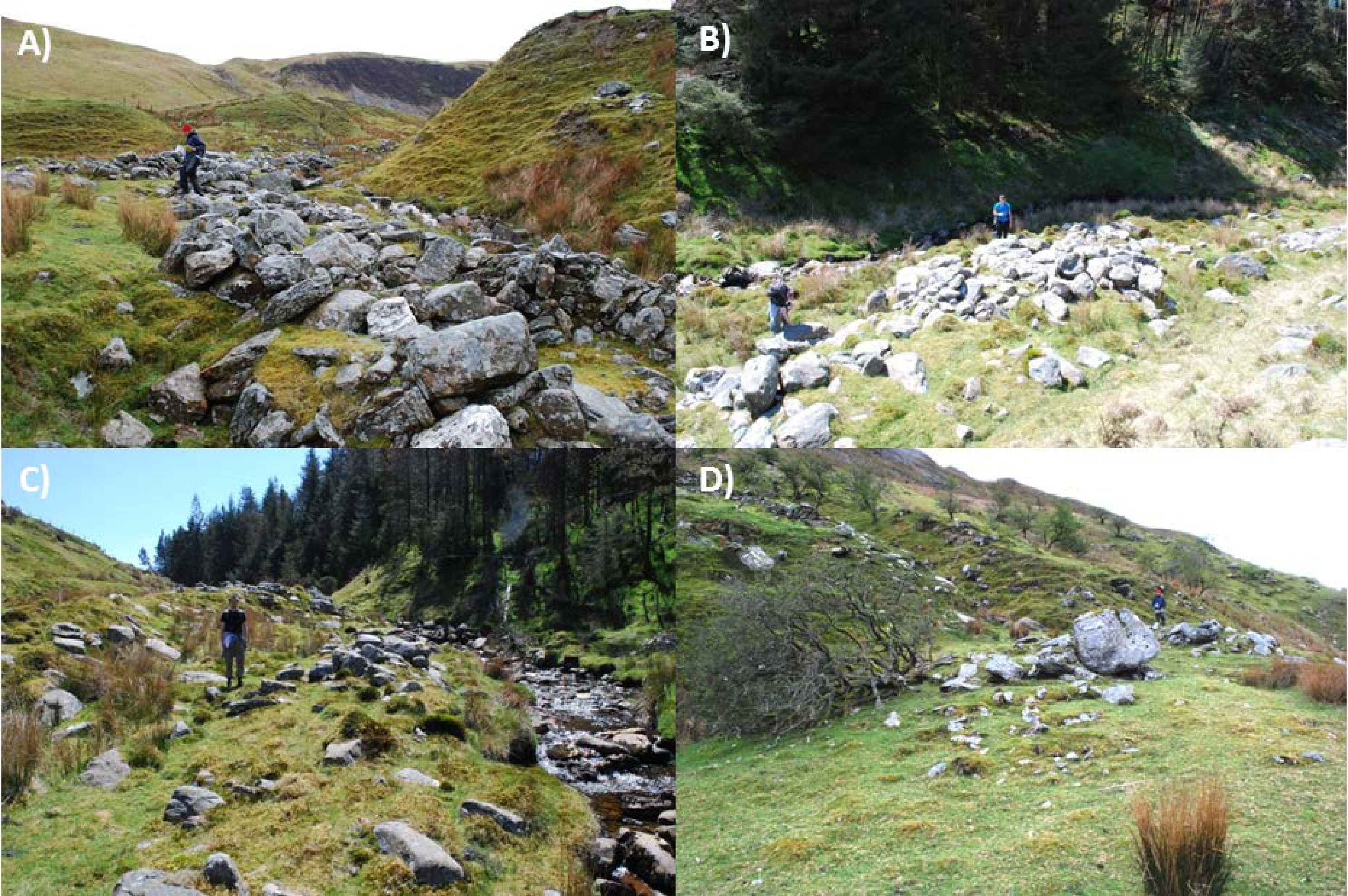
Aberystwyth
560 m Bryn Llychese
Cambrian
610 m Pen y Garn
Mountains
Afon Ystwyth
Hafod
3
2
571 m Geifas
1
Ysbyty Ystwyth
554 m Domen Milwyn
ii)
a
Study catchments
b
c
a - Snowdonia
b - Cambrian Mountians
c - Brecon Beacons
i)
Snowdonia
Leri
Rheidol
Ystwyth
Cambrian Mountains
Study subcatchments
1 - Nant Gau
2 - Nant Milwyn
3 - Nant Cwm-Du
Elevation (m AOD)
0-100
100-200
200-300
300-400
400-500
500-610
N
0
2.5
5
Kilometers
Graveyard
Summit


A)
July rain r = -0.696**
August rain r = -0.643**
Cwmystwyth rainfall (mm)
300
200
100
B)
July max GDF r = -0.651**
July mean GDF r = -0.761**
Cwmystwyth max GDF (m3 s-1)
Cwmystwyth mean GDF (m3 s-1)
15
10
5
5.0
4.0
3.0
2.0
1.0
C)
Aug Max GDF
r = -0.476*
Aug mean GDF
r = -0.626**
Cwmystwyth max GDF (m3 s-1)
Cwmystwyth mean GDF (m3 s-1)
15
10
5
0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
SNAO

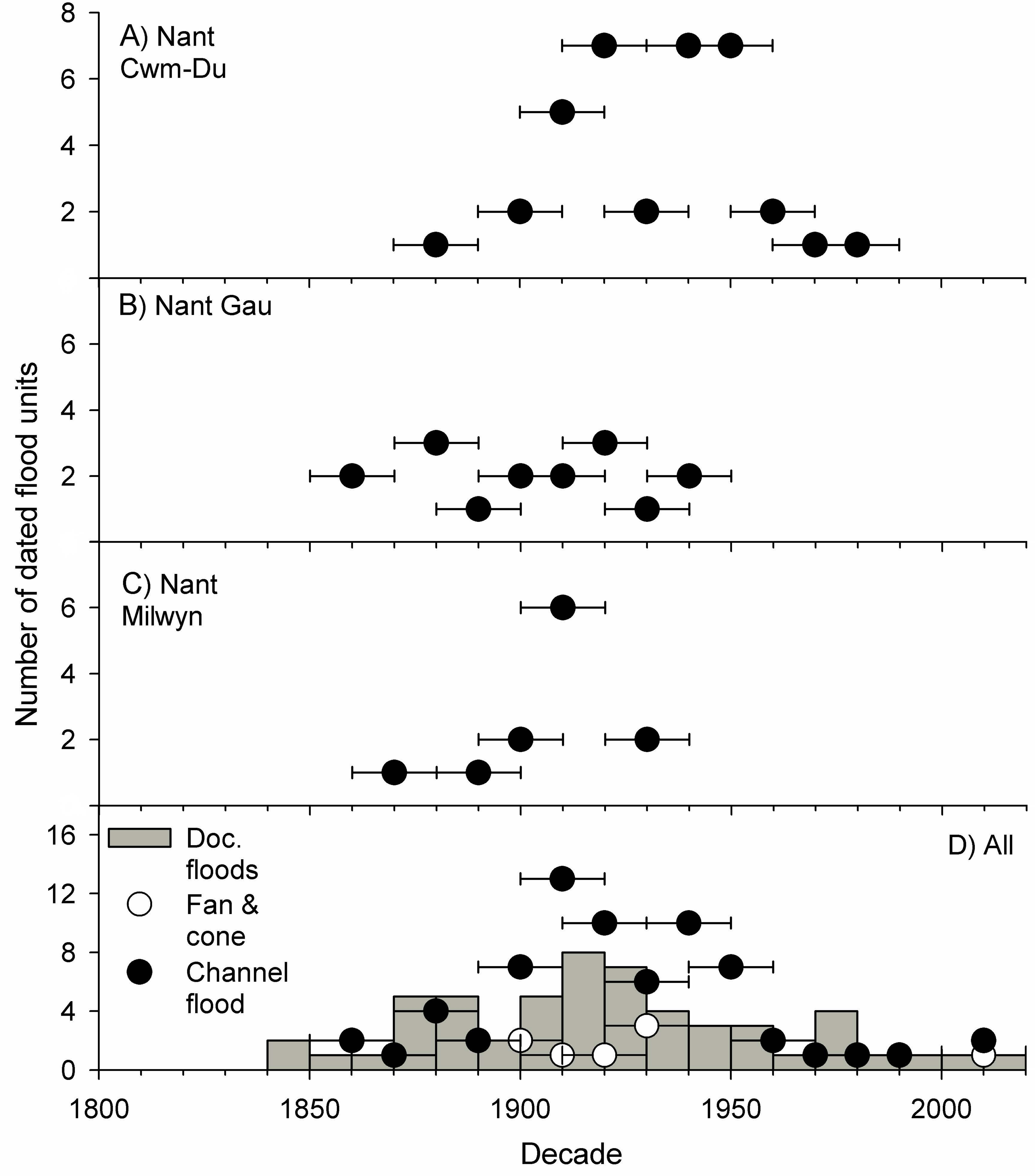

JA SNAO
Smoothed SNAO
Berm date
(A)
SNAO
1.5
1.0
0.5
0.0
-0.5
-1.0
16
14
12
10
8
6
4
2
JA cyclonic LWT
LWT smooth
Berm date
JA SWEP
smooth
(B)
JA cyclonic LWT frequency
20
15
10
5
Number of dated boulder-berms
JA SWEP smooth (mm)
220
200
180
160
140
120
NF NAO
NAO smooth
NF SWEP smooth
(C)
Nov-Feb NAO
4
3
2
1
0
-1
-2
-3
NF SWEP smooth (mm)
480
460
440
420
400
380
360
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year



Cambrian Mountains, Mid-Wales
Brecon Beacons, South Wales
Dartmoor, South West England
Northern Pennines, North East England
25
28
Lake District,
North West England
Yorkshire Dales, Northern England
England and Wales, all regions
Number of dated flood units
Number of dated flood units
Number of dated flood units
Decade beginning (AD)
1600
1650
1700
1750
1800
1850
1900
1950
2000


A)
B)
C)
D)

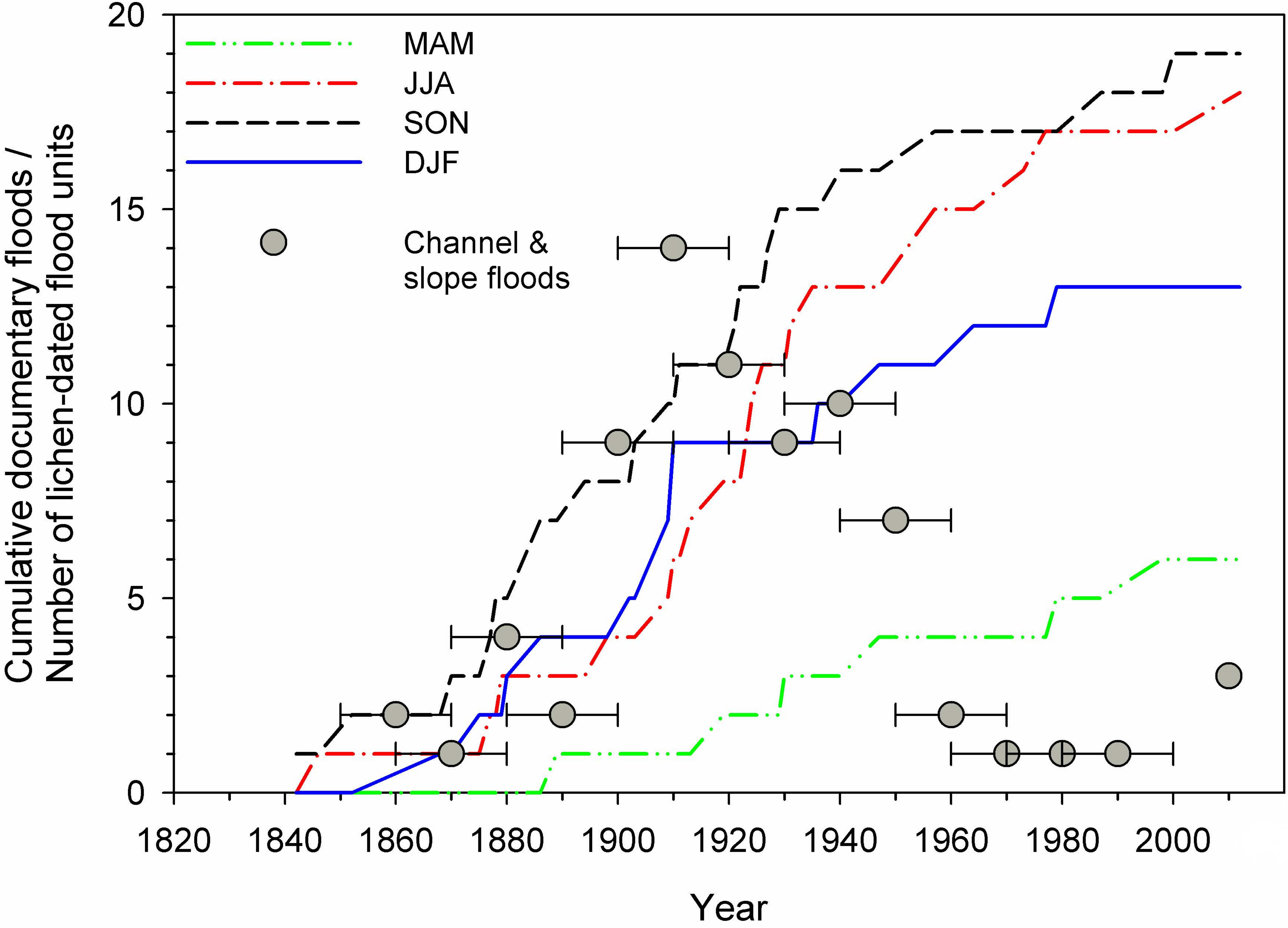

(A)
P. tuberculosa
R. geographicum
y = 0.6682x + 25.714
R2 = 0.8956
y = 0.2814x + 3.6796
R2 = 0.9075
Lichen diameter (mm)
Surface age (years)
0
20
40
60
80
100
120
140
160
(B)
LL method
5LL method
3LL method
Predicted age difference from true age (years)
True gravestone age (years)
0
5
10
15
20
25
30
35
180
200



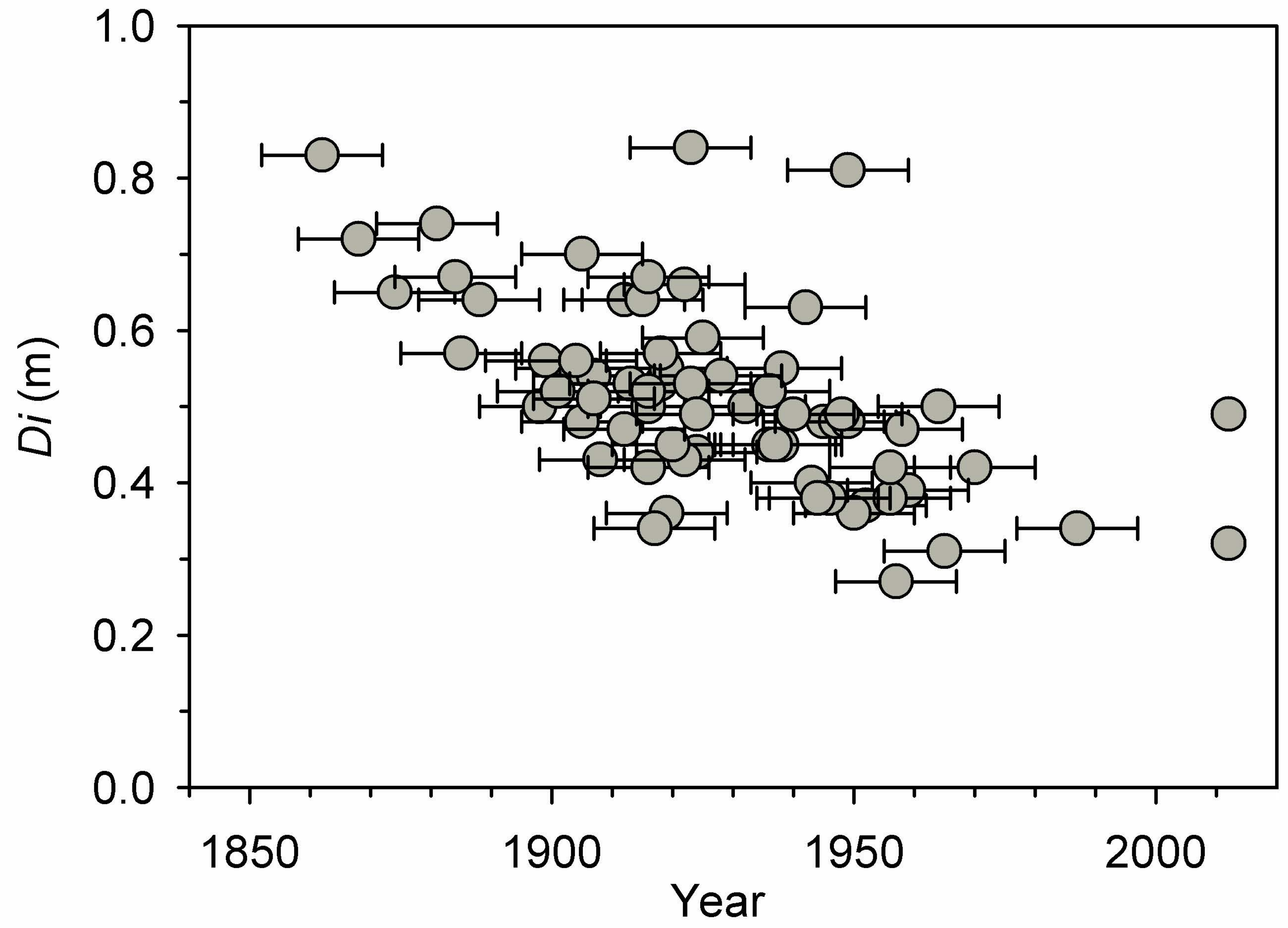
A) Nant
Cwm-Du
B) Nant Gau
C) Nant
Milwyn
D) All
Doc.
floods
Fan &
cone
Channel
flood
Number of dated flood units
Decade
0
2
4
6
8
12
16
1800
1850
1900
1950
2000

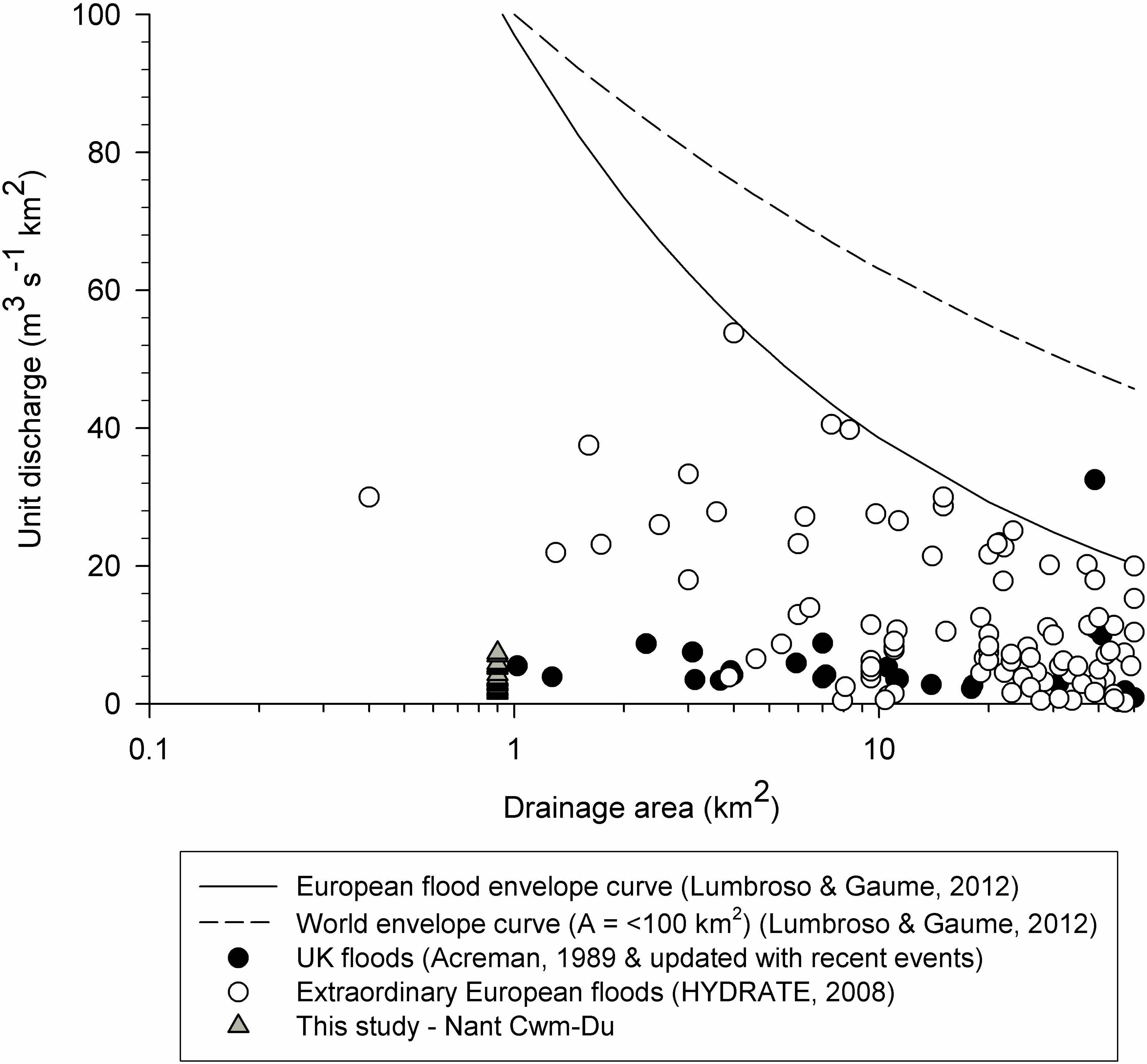

Vegetated erosion scars

Active channel
Low terrace and 1930s boulder berm
Floodplain and 2012
boulder berm



20
15
10
5
0
Cumulative documentary floods /
Number of lichen-dated flood units
MAM
JJA
SON
DJF
Channel &
slope floods
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year


1.0
0.8
0.6
0.4
0.2
0.0
Di (m)
1850
1900
1950
2000
Year



Unit discharge ($m^3 s^{-1} km^2$)
100
80
60
40
20
0
0.1
1
10
Drainage area (km^2)
European flood envelope curve (Lumbroso & Gaume, 2012)
World envelope curve (A = <100 km^2) (Lumbroso & Gaume, 2012)
UK floods (Acreman, 1989 & updated with recent events)
Extraordinary European floods (HYDRATE, 2008)
This study - Nant Cwm-Du

JA SNAO
Smoothed SNAO
Berm date
(A)
SNAO
JA cyclonic LWT
LWT smooth
Berm date
JA SWEP
smooth
(B)
JA cyclonic LWT frequency
Number of dated boulder-berms
JA SWEP smooth (mm)
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000